TM No. 841072





NAVAL UNDERWATER SYSTEMS CENTER
NEW LONDON LABORATORY
NEW LONDON, CONNECTICUT 06320

TECHNICAL MEMORANDUM

# DIELECTRIC PROPERTIES OF PIEZOELECTRIC POLYVINYLIDENE FLUORIDE (PVDF)

Date: April 16, 1984

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REFERENCE ONLY

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**16 APR 1984** | 2. REPORT TYPE<br>**Technical Memo** | 3. DATES COVERED<br>**16-04-1984 to 16-04-1984** |

4. TITLE AND SUBTITLE
**Dielectric Properties of Piezoelectric Polyvinylidene Fluoride (PVDF)**

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
**Mark Moffett; James Powers**

5d. PROJECT NUMBER
**A61404**

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
**Naval Underwater Systems Center,New London,CT,06320**

8. PERFORMING ORGANIZATION REPORT NUMBER
**TM 841072**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
**NAVMAT**

10. SPONSOR/MONITOR'S ACRONYM(S)
**NAVMAT 05B**

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES
**NUWC2015**

14. ABSTRACT
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15. SUBJECT TERMS
**piezoelectricity; polyvinylidene fluoride; PVDF**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **21** | |

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## ABSTRACT

Measurements were made of the free dielectric constant and the dielectric loss tangent of piezoelectric polyvinylidene fluoride (PVDF) at frequencies between 1 kHz and 5 MHz and temperatures between -28°C and +51°C. Samples of nonvoided and voided PVDF were tested. The dielectric constant increases with increasing temperature and/or decreasing frequency, ranging from about 3 to 11 for the voided material and from about 4 to 14 for the nonvoided material. The dielectric loss tangent (dissipation factor) ranged from about 0.02 at low frequencies and high temperatures to about 0.3 at high frequencies and high temperatures. The voided material was not as lossy as the nonvoided material, with maximum values ~ 0.2 for the voided material and 0.3 for the nonvoided material. A slight temperature aging effect was observed; an increase of a few percent in dielectric constant resulted from cycling the samples to 51°C.

## ADMINISTRATIVE INFORMATION

This memorandum was prepared under Job Order No. A61404, "Broadband Hydrophone for Transient Measurements," Principal Investigator: Dr. M. B. Moffett, Code 3321, Associate Investigator: J. M. Powers, Code 3234, Sponsoring Activity: NAVMAT 05B (CAPT Z. L. Newcomb), NUSC IED Program, Program Manager: Dr. K. M. Lima, Code 101. The authors are located at the Naval Underwater Systems Center, New London, CT 06320.

# I. INTRODUCTION

Piezoelectric polyvinylidene fluoride (PVDF) is a useful hydrophone-element material because of its shock resistance, low density, and low mechanical impedance.[1,2] However, the capacitance is about 100 times less than that of piezoelectric ceramics, so that capacitive coupling loss is more likely to be a problem with PVDF hydrophone designs than with conventional lead zirconate-titanate (PZT) hydrophones. Furthermore, PVDF is a much lossier material than PZT,[3-5] a fact which appears to preclude its use in underwater projectors.[6] The dielectric constant and dissipation factor of PVDF have been measured at room temperature by Pennwalt workers[7] to about 400 kHz. Callerame, Tancrell and Wilson,[3] interested in medical ultrasonic applications, extended the frequency range to 20 MHz. Further extension to 100 MHz was provided by Leung and Yung[4] and by Chen.[5] All of these measurements were made on nonvoided material at room temperature. Because of the importance of the temperature dependence, we decided to measure the dielectric constant and dissipation factor as a function of temperature as well as frequency. The advent of thick-film, voided PVDF[8] made it desirable to perform the same measurements on the newer material as well.

# II. EXPERIMENT

Two samples of PVDF were tested: 1) a nonvoided 2.5 cm x 2.5 cm x 0.11 mm, nickle-aluminum electroded Kynar® element manufactured by Pennwalt Corporation,[7] and 2) a voided 6.3 cm x 6.3 cm x 0.64 mm element, serial number AC 47/3, manufactured by Thorn EMI, Limited.[8] The voided element had electroplated copper electrodes. The sample under test was held by a specially-made alligator clip making separate electrical contact with each electrode. A 3-ft length of RG-58C/U cable passing through a cloth insulator served as the electrical feedthrough into the temperature-controlled environment. The latter was provided by a Tenney Junior oven/refrigerator unit. All impedance measurements were made with a Hewlett-Packard 4192A low-frequency impedance analyzer with a 16095A probe fixture operated in a single-ended mode.

The impedance of the connecting cable was accounted for after measurement of the impedances, $Z_{sc}$ and $Z_{oc}$, with the alligator clip contacts short-circuited and open-circuited, respectively. If the cable is assumed to behave as a uniform transmission line, the element impedance, Z, can be calculated from the measured impedance, $Z_{in}$ (with element and cable in place), as follows:

$$Z = Z_{oc}\,(Z_{in} - Z_{sc})/(Z_{oc} - Z_{in}) \tag{1}$$

The element capacitance is then

$$C = \mathrm{Im}(Z^{-1})/2\pi f, \tag{2}$$

where f is the frequency. The dissipation factor is

$$D = \mathrm{Re}(Z^{-1})/\mathrm{Im}(Z^{-1}) = -\mathrm{Re}(Z)/\mathrm{Im}(Z). \tag{3}$$

The (free) dielectric constant, $\varepsilon_{33}^{T}/\varepsilon_0$ was determined from the capacitance, C, as

$$\varepsilon_{33}^{T}/\varepsilon_0 = C/C_0 = Ct/\varepsilon_0 A \tag{4}$$

where $C_0$ is the capacitance of an air gap dimensionally equal to the element size, $\varepsilon_0$ is the permittivity of free space, 8.85pF/m, t is the element thickness and A the element area. $C_0$ was 50.3pF for the nonvoided element and 54.9pF for the voided one.

The samples were subjected to the temperature history depicted in Figure 1. The material was considered to be "virgin" during the first 22°C to 31°C to -27°C cycle, but a rise in capacitance of several percent was noted after cycling (and holding for about 2 hrs) to 51°C and so data obtained after that point are for "aged" material.

## III. RESULTS

The element capacitances are given in Table I. After division by $C_0$ (see Eq. 4), the dielectric constants of Table II and Figures 2-5 were obtained. It can be seen that the dielectric constant decreases monotonically with increasing frequency and with decreasing temperature. In fact, over the range of frequencies and temperatures in this study, the dielectic constant changed by a factor of more than three. The dielectric constant of the nonvoided material was generally higher than that of the voided material.

The dielectric loss tangents are given in Table III and Figures 6-9. There is a broad maximum in the loss tangent which shifts upward in frequency as the temperature is raised. At low temperatures, the voided material exhibited a sharp peak in loss factor at about 1 MHz. (It should be noted that since most of the measurements were made in a 1-2-5 frequency sequence, there is a possibility that other sharp peaks of this type existed but escaped unnoticed between the large frequency steps.) A similar "resonance" has been observed by workers at Thorn EMI.[9]

## IV. DISCUSSION

The dielectric constant and dissipation factor curves of Figures 2-9 have the general shape of a dielectric relaxation process. However, each of these curves changes too slowly with frequency to be described by a single relaxation time, i.e., a multiplicity of relaxation times must be involved. Another way of seeing this result is that since the relaxation time, $\tau$, of a conductive dielectric is given by[10] $\tau = \varepsilon/\sigma$, where $\sigma$ is the electrical conductivity, and since we can express the conductivity, $\sigma$, as $2\pi f\varepsilon D$, then the relaxation time, $\tau$, would be given by $(2\pi f D)^{-1}$. In other words, to be describable by a single (constant) relaxation time, $\tau$, the dissipation factor, D, would have to be inversely proportional to frequency. This is clearly not the case, as can be seen in Figures 6-9.

## V. CONCLUSIONS

The free dielectric constant of nonvoided PVDF ranges from about 4 to 14 over the -28°C to 51°C temperature range and 1 kHz to 5 MHz frequency range, with a value of approximately 12 at 1kHz and room temperature. (This compares reasonably well with literature values.[7,11]) The voided material has a lower dielectric constant, ranging from about 3 to 11 over the temperature and frequency ranges considered here.

The voided material is not as lossy as the nonvoided material. The maximum dissipation factor was about 0.2 for the voided material and 0.3 for the nonvoided sample. At room temperature and 1 kHz, the dissipation factor was about 0.012 for each material.

After cycling to 51°C, the dielectric constant was elevated a few percent, but the dissipation factor was essentially unchanged.

## VI. ACKNOWLEDGMENTS

The authors wish to thank W. L. Clay for the use of the oven/refrigerator unit, G. R. Giordano and J. F. Lindberg for the use of the impedance analyzer and accessories, and A. P. Sullivan for the use of the sample holder.

| T(°C) \ f(kHz) | 1 | 2 | 5 | 10 | 20 | 50 | 100 | 200 | 500 | 1000 | 2000 | 5000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 616.7 | 613.7 | 609.6 | 605.0 | 591.4 | 575.6 | 566.6 | 546.9 | 509.4 | 468.8 | 420.1 | 350.8 | |
| 22 | 602.7 | 599.7 | 592.6 | 586.0 | 580.4 | 549.6 | 532.6 | 504.0 | 454.7 | 408.9 | 362.5 | 304.7 | virgin |
| 11 | 576.7 | 571.7 | 562.6 | 551.0 | 537.4 | 495.6 | 471.6 | 435.0 | 383.0 | 342.8 | 306.2 | 265.5 | nonvoided |
| 2 | 552.7 | 543.7 | 526.6 | 507.0 | 481.4 | 433.6 | 402.6 | 365.1 | 321.2 | 290.4 | 264.9 | 236.7 | element |
| -8 | 501.7 | 482.7 | 451.6 | 423.0 | 392.4 | 348.6 | 320.6 | 294.1 | 265.3 | 246.8 | 230.2 | 212.5 | $C_o = 50.3$ |
| -17 | 418.7 | 395.7 | 362.6 | 337.0 | 313.4 | 283.6 | 265.7 | 249.1 | 230.4 | 219.1 | 208.9 | 196.2 | pF |
| -27 | 318.7 | 302.7 | 281.6 | 266.0 | 252.4 | 237.6 | 225.7 | 216.1 | 205.4 | 199.2 | 192.5 | 183.9 | |
| 51 | 681.7 | 676.7 | 670.6 | 665.0 | 663.4 | 634.6 | 630.6 | 620.9 | 600.9 | 577.5 | 543.5 | 474.2 | |
| 41 | 656.7 | 653.7 | 647.6 | 643.0 | 644.4 | 617.6 | 604.6 | 594.9 | 569.1 | 537.5 | 493.0 | 412.0 | aged |
| 31 | 639.7 | 635.7 | 629.6 | 624.0 | 617.4 | 593.6 | 579.6 | 562.9 | 525.3 | 485.5 | 435.1 | 361.3 | nonvoided |
| 22 | 619.7 | 614.7 | 607.6 | 600.0 | 591.4 | 562.6 | 543.6 | 517.0 | 467.6 | 421.7 | 372.0 | 311.3 | element |
| 11 | 587.7 | 582.7 | 572.6 | 560.0 | 543.4 | 505.6 | 477.6 | 440.0 | 385.9 | 343.8 | 306.2 | 263.6 | $C_o = 50.3$ |
| 2 | 559.7 | 549.7 | 531.6 | 512.0 | 486.4 | 436.6 | 404.6 | 367.1 | 321.2 | 290.4 | 264.0 | 235.3 | pF |
| -9 | 504.7 | 486.7 | 454.6 | 425.0 | 394.4 | 349.6 | 321.6 | 294.1 | 264.3 | 245.8 | 229.2 | 211.0 | |
| -17 | 421.7 | 398.7 | 363.6 | 338.0 | 313.4 | 283.6 | 264.7 | 248.1 | 229.4 | 218.1 | 207.0 | 195.4 | |
| -28 | 317.7 | 300.7 | 279.6 | 265.0 | 251.4 | 235.6 | 224.7 | 215.1 | 204.4 | 197.3 | 190.5 | 182.3 | |
| 31 | 516.7 | 514.7 | 511.6 | 506.0 | 496.4 | 488.6 | 478.6 | 463.0 | 435.7 | 401.9 | 367.8 | 316.6 | |
| 22 | 505.7 | 502.7 | 497.6 | 491.0 | 478.4 | 466.6 | 449.6 | 428.0 | 391.9 | 355.6 | 322.3 | 279.6 | virgin |
| 11 | 481.7 | 477.7 | 470.6 | 463.0 | 444.4 | 424.6 | 402.6 | 375.1 | 338.1 | 305.2 | 280.2 | 248.4 | voided |
| 2 | 460.7 | 453.7 | 440.6 | 426.0 | 402.4 | 374.6 | 349.6 | 323.1 | 291.2 | 265.6 | 247.5 | 224.4 | element |
| -8 | 418.7 | 404.7 | 381.6 | 361.0 | 336.4 | 309.6 | 289.6 | 270.1 | 248.3 | 230.0 | 219.5 | 204.2 | $C_o = 54.9$ |
| -17 | 359.7 | 342.7 | 319.6 | 301.0 | 282.4 | 261.6 | 248.7 | 236.1 | 221.4 | 207.2 | 202.1 | 191.2 | pF |
| -27 | 286.7 | 274.7 | 259.6 | 248.0 | 238.4 | 224.6 | 216.7 | 209.2 | 200.5 | 193.3 | 187.6 | 179.7 | |
| 51 | 581.7 | 578.7 | 574.6 | 570.0 | 558.4 | 552.6 | 545.6 | 535.9 | 523.3 | 499.1 | 473.6 | 422.5 | |
| 41 | 553.7 | 550.7 | 546.6 | 541.0 | 531.4 | 525.6 | 518.6 | 508.0 | 489.4 | 461.8 | 430.8 | 374.2 | aged |
| 31 | 542.7 | 539.7 | 534.6 | 531.0 | 519.4 | 510.6 | 499.6 | 484.0 | 456.6 | 421.6 | 385.8 | 330.9 | voided |
| 22 | 524.7 | 521.7 | 516.6 | 509.0 | 496.4 | 483.6 | 468.6 | 446.0 | 409.8 | 371.4 | 335.6 | 290.6 | element |
| 11 | 498.7 | 493.7 | 485.6 | 476.0 | 459.4 | 437.6 | 413.6 | 386.1 | 345.1 | 311.2 | 284.1 | 250.9 | $C_o = 54.9$ |
| 2 | 474.7 | 466.7 | 452.6 | 437.0 | 414.4 | 383.6 | 357.6 | 329.1 | 295.2 | 268.6 | 249.5 | 226.1 | pF |
| -9 | 429.7 | 415.7 | 391.6 | 370.0 | 343.4 | 314.6 | 292.6 | 272.1 | 249.3 | 230.0 | 219.5 | 204.3 | |
| -17 | 366.7 | 348.7 | 323.6 | 305.0 | 284.4 | 263.6 | 249.7 | 236.1 | 221.4 | 207.2 | 201.2 | 190.4 | |
| -28 | 288.7 | 276.7 | 260.6 | 248.0 | 237.4 | 224.6 | 216.7 | 208.2 | 199.5 | 192.3 | 186.6 | 178.9 | |

Table I. Capacitance, C, of PVDF elements (picofarads).

| T(°C) \ f(kHz) | 1 | 2 | 5 | 10 | 20 | 50 | 100 | 200 | 500 | 1000 | 2000 | 5000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 12.3 | 12.2 | 12.1 | 12.0 | 11.8 | 11.4 | 11.3 | 10.9 | 10.1 | 9.3 | 8.4 | 7.0 | |
| 22 | 12.0 | 11.9 | 11.8 | 11.6 | 11.5 | 10.9 | 10.6 | 10.0 | 9.0 | 8.1 | 7.2 | 6.1 | virgin |
| 11 | 11.5 | 11.4 | 11.2 | 11.0 | 10.7 | 9.9 | 9.4 | 8.6 | 7.6 | 6.8 | 6.1 | 5.3 | nonvoided |
| 2 | 11.0 | 10.8 | 10.5 | 10.1 | 9.6 | 8.6 | 8.0 | 7.3 | 6.4 | 5.8 | 5.3 | 4.7 | element |
| -8 | 10.0 | 9.6 | 9.0 | 8.4 | 7.8 | 6.9 | 6.4 | 5.8 | 5.3 | 4.9 | 4.6 | 4.2 | |
| -17 | 8.3 | 7.9 | 7.2 | 6.7 | 6.2 | 5.6 | 5.3 | 5.0 | 4.6 | 4.4 | 4.2 | 3.9 | |
| -27 | 6.3 | 6.0 | 5.6 | 5.3 | 5.0 | 4.7 | 4.5 | 4.3 | 4.1 | 4.0 | 3.8 | 3.7 | |
| 51 | 13.6 | 13.5 | 13.3 | 13.2 | 13.2 | 12.6 | 12.5 | 12.3 | 11.9 | 11.5 | 10.8 | 9.4 | |
| 41 | 13.1 | 13.0 | 12.9 | 12.8 | 12.8 | 12.3 | 12.0 | 11.8 | 11.3 | 10.7 | 9.8 | 8.2 | aged |
| 31 | 12.7 | 12.6 | 12.5 | 12.4 | 12.3 | 11.8 | 11.5 | 11.2 | 10.4 | 9.7 | 8.6 | 7.2 | nonvoided |
| 22 | 12.3 | 12.2 | 12.1 | 11.9 | 11.8 | 11.2 | 10.8 | 10.3 | 9.3 | 8.4 | 7.4 | 6.2 | element |
| 11 | 11.7 | 11.6 | 11.4 | 11.1 | 10.8 | 10.0 | 9.5 | 8.7 | 7.7 | 6.8 | 6.1 | 5.2 | |
| 2 | 11.1 | 10.9 | 10.6 | 10.2 | 9.7 | 8.7 | 8.0 | 7.3 | 6.4 | 5.8 | 5.2 | 4.7 | |
| -9 | 10.0 | 9.7 | 9.0 | 8.4 | 7.8 | 6.9 | 6.4 | 5.8 | 5.3 | 4.9 | 4.6 | 4.2 | |
| -17 | 8.4 | 7.9 | 7.2 | 6.7 | 6.2 | 5.6 | 5.3 | 4.9 | 4.6 | 4.3 | 4.1 | 3.9 | |
| -28 | 6.3 | 6.0 | 5.6 | 5.3 | 5.0 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.8 | 3.6 | |
| 31 | 9.4 | 9.4 | 9.3 | 9.2 | 9.0 | 8.9 | 8.7 | 8.4 | 7.9 | 7.3 | 6.7 | 5.8 | |
| 22 | 9.2 | 9.2 | 9.1 | 8.9 | 8.7 | 8.5 | 8.2 | 7.8 | 7.1 | 6.5 | 5.9 | 5.1 | virgin |
| 11 | 8.8 | 8.7 | 8.6 | 8.4 | 8.1 | 7.7 | 7.3 | 6.8 | 6.2 | 5.6 | 5.1 | 4.5 | voided |
| 2 | 8.4 | 8.3 | 8.0 | 7.8 | 7.3 | 6.8 | 6.4 | 5.9 | 5.3 | 4.8 | 4.5 | 4.1 | element |
| -8 | 7.6 | 7.4 | 6.9 | 6.6 | 6.1 | 5.6 | 5.3 | 4.9 | 4.5 | 4.2 | 4.0 | 3.7 | |
| -17 | 6.6 | 6.2 | 5.8 | 5.5 | 5.1 | 4.8 | 4.5 | 4.3 | 4.0 | 3.8 | 3.7 | 3.5 | |
| -27 | 5.2 | 5.0 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.8 | 3.7 | 3.5 | 3.4 | 3.3 | |
| 51 | 10.6 | 10.5 | 10.5 | 10.4 | 10.2 | 10.1 | 9.9 | 9.8 | 9.5 | 9.1 | 8.6 | 7.7 | |
| 41 | 10.1 | 10.0 | 10.0 | 9.9 | 9.7 | 9.6 | 9.4 | 9.3 | 8.9 | 8.4 | 7.8 | 6.8 | aged |
| 31 | 9.9 | 9.8 | 9.7 | 9.7 | 9.5 | 9.3 | 9.1 | 8.8 | 8.3 | 7.7 | 7.0 | 6.0 | voided |
| 22 | 9.6 | 9.5 | 9.4 | 9.3 | 9.0 | 8.8 | 8.5 | 8.1 | 7.5 | 6.8 | 6.1 | 5.3 | element |
| 11 | 9.1 | 9.0 | 8.8 | 8.7 | 8.4 | 8.0 | 7.5 | 7.0 | 6.3 | 5.7 | 5.2 | 4.6 | |
| 2 | 8.6 | 8.5 | 8.2 | 8.0 | 7.5 | 7.0 | 6.5 | 6.0 | 5.4 | 4.9 | 4.5 | 4.1 | |
| -9 | 7.8 | 7.6 | 7.1 | 6.7 | 6.3 | 5.7 | 5.3 | 5.0 | 4.5 | 4.2 | 4.0 | 3.7 | |
| -17 | 6.7 | 6.4 | 5.9 | 5.6 | 5.2 | 4.8 | 4.5 | 4.3 | 4.0 | 3.8 | 3.7 | 3.5 | |
| -28 | 5.3 | 5.0 | 4.7 | 4.5 | 4.3 | 4.1 | 3.9 | 3.8 | 3.6 | 3.5 | 3.4 | 3.3 | |

Table II. Dielectric constant, $\varepsilon_{33}^{T}/\varepsilon_0$ of PVDF elements.

| T(°C) \ f(kHz) | 1 | 2 | 5 | 10 | 20 | 50 | 100 | 200 | 500 | 1000 | 2000 | 5000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | .011 | .015 | .019 | .025 | .039 | .055 | .075 | .101 | .151 | .199 | .248 | .305 | |
| 22 | .012 | .019 | .026 | .035 | .055 | .079 | .109 | .139 | .192 | .229 | .258 | .282 | virgin |
| 11 | .020 | .028 | .043 | .059 | .080 | .126 | .152 | .185 | .220 | .236 | .243 | .241 | nonvoided |
| 2 | .035 | .050 | .074 | .098 | .127 | .171 | .188 | .206 | .214 | .212 | .204 | .193 | element |
| −8 | .074 | .096 | .126 | .148 | .168 | .195 | .187 | .184 | .174 | .162 | .152 | .143 | |
| −17 | .117 | .134 | .150 | .156 | .160 | .168 | .148 | .140 | .128 | .117 | .111 | .107 | |
| −27 | .118 | .123 | .123 | .119 | .116 | .112 | .099 | .095 | .086 | .082 | .080 | .085 | |
| 51 | .016 | .018 | .019 | .023 | .030 | .043 | .045 | .058 | .086 | .122 | .174 | .274 | |
| 41 | .014 | .016 | .019 | .023 | .040 | .042 | .055 | .073 | .113 | .161 | .225 | .333 | aged |
| 31 | .014 | .018 | .023 | .028 | .040 | .055 | .073 | .099 | .149 | .197 | .249 | .312 | nonvoided |
| 22 | .016 | .021 | .029 | .039 | .054 | .080 | .106 | .138 | .192 | .234 | .269 | .301 | element |
| 11 | .022 | .031 | .046 | .062 | .086 | .125 | .155 | .190 | .226 | .244 | .253 | .261 | |
| 2 | .037 | .052 | .076 | .100 | .130 | .175 | .192 | .210 | .219 | .218 | .211 | .204 | |
| −9 | .075 | .098 | .128 | .151 | .171 | .199 | .191 | .188 | .178 | .167 | .158 | .154 | |
| −17 | .118 | .135 | .151 | .159 | .162 | .175 | .151 | .143 | .131 | .120 | .114 | .113 | |
| −28 | .118 | .123 | .123 | .120 | .116 | .116 | .099 | .095 | .087 | .082 | .080 | .085 | |
| 31 | .010 | .015 | .020 | .026 | .033 | .049 | .066 | .092 | .133 | .168 | .200 | .231 | |
| 22 | .012 | .018 | .025 | .034 | .046 | .068 | .092 | .123 | .164 | .191 | .206 | .218 | virgin |
| 11 | .019 | .028 | .042 | .058 | .077 | .105 | .130 | .157 | .131 | .194 | .194 | .188 | voided |
| 2 | .033 | .047 | .069 | .090 | .111 | .139 | .154 | .168 | .174 | .175 | .163 | .151 | element |
| −8 | .066 | .085 | .110 | .126 | .142 | .148 | .150 | .149 | .141 | .140 | .123 | .112 | |
| −17 | .097 | .110 | .121 | .127 | .136 | .126 | .121 | .115 | .107 | .119 | .092 | .084 | |
| −27 | .092 | .097 | .099 | .098 | .097 | .090 | .083 | .078 | .074 | .111 | .063 | .061 | |
| 51 | .015 | .017 | .020 | .022 | .024 | .030 | .039 | .051 | .079 | .104 | .142 | .206 | |
| 41 | .013 | .015 | .018 | .023 | .026 | .034 | .046 | .064 | .098 | .131 | .173 | .231 | aged |
| 31 | .014 | .018 | .023 | .028 | .034 | .049 | .065 | .090 | .132 | .169 | .205 | .245 | voided |
| 22 | .015 | .021 | .029 | .037 | .048 | .070 | .093 | .123 | .166 | .197 | .217 | .235 | element |
| 11 | .022 | .030 | .044 | .059 | .077 | .107 | .133 | .161 | .190 | .203 | .202 | .200 | |
| 2 | .034 | .048 | .071 | .092 | .113 | .143 | .160 | .176 | .183 | .183 | .171 | .163 | |
| −9 | .069 | .087 | .113 | .130 | .146 | .156 | .156 | .156 | .149 | .146 | .129 | .120 | |
| −17 | .101 | .114 | .127 | .133 | .140 | .134 | .125 | .121 | .110 | .120 | .095 | .091 | |
| −28 | .096 | .101 | .104 | .101 | .102 | .093 | .086 | .082 | .075 | .110 | .065 | .065 | |

Table III. Dissipation factor, D, of PVDF elements.

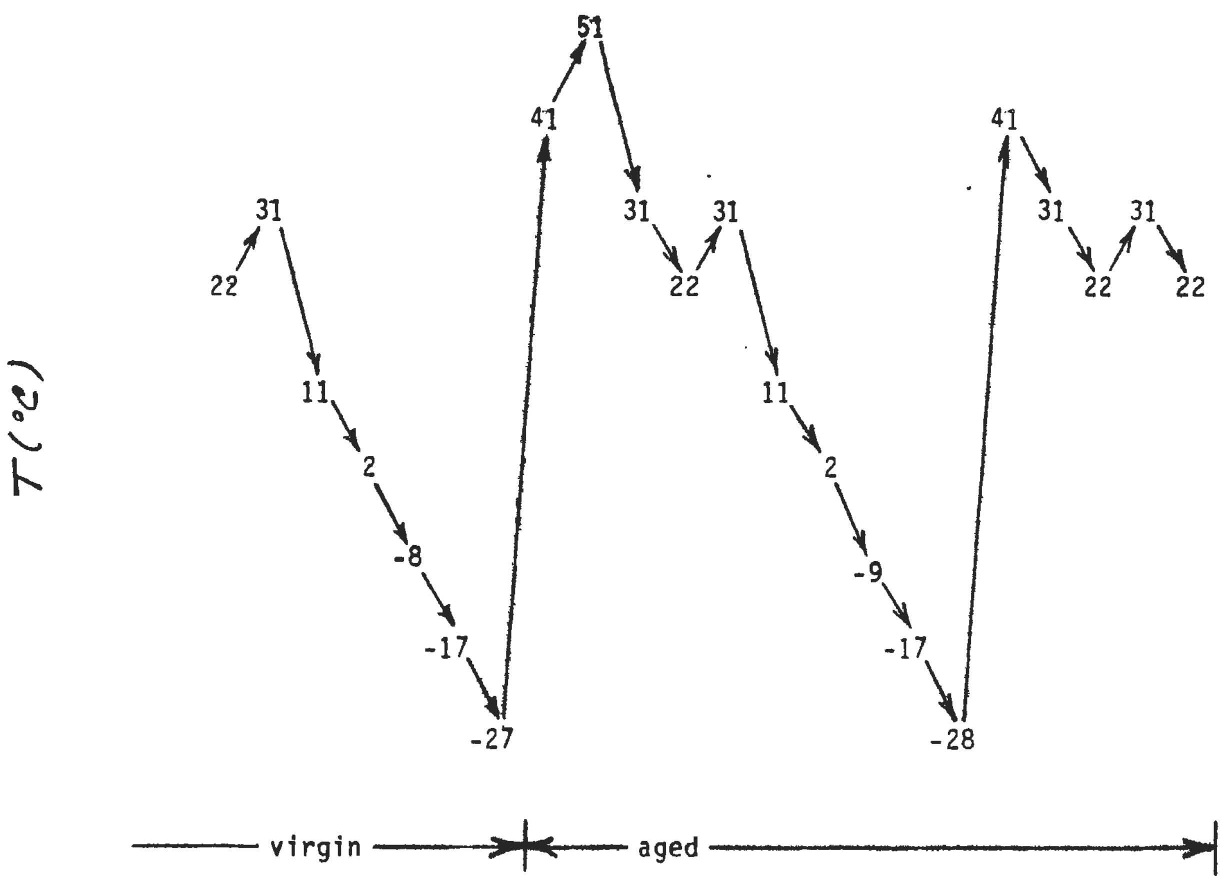


Figure 1. Temperature history of PVDF samples.

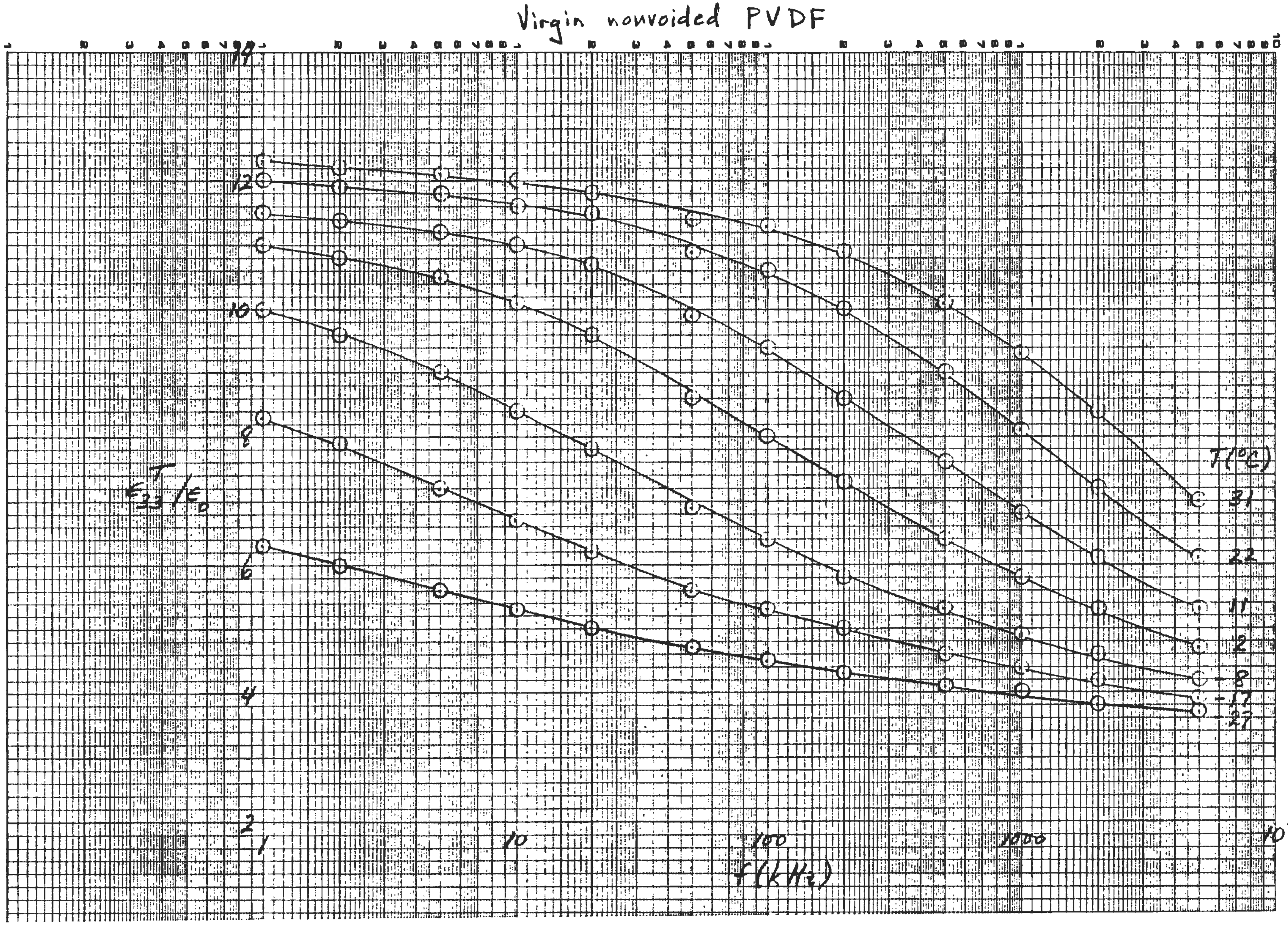


Figure 2. Dielectric constant, virgin nonvoided PVDF.

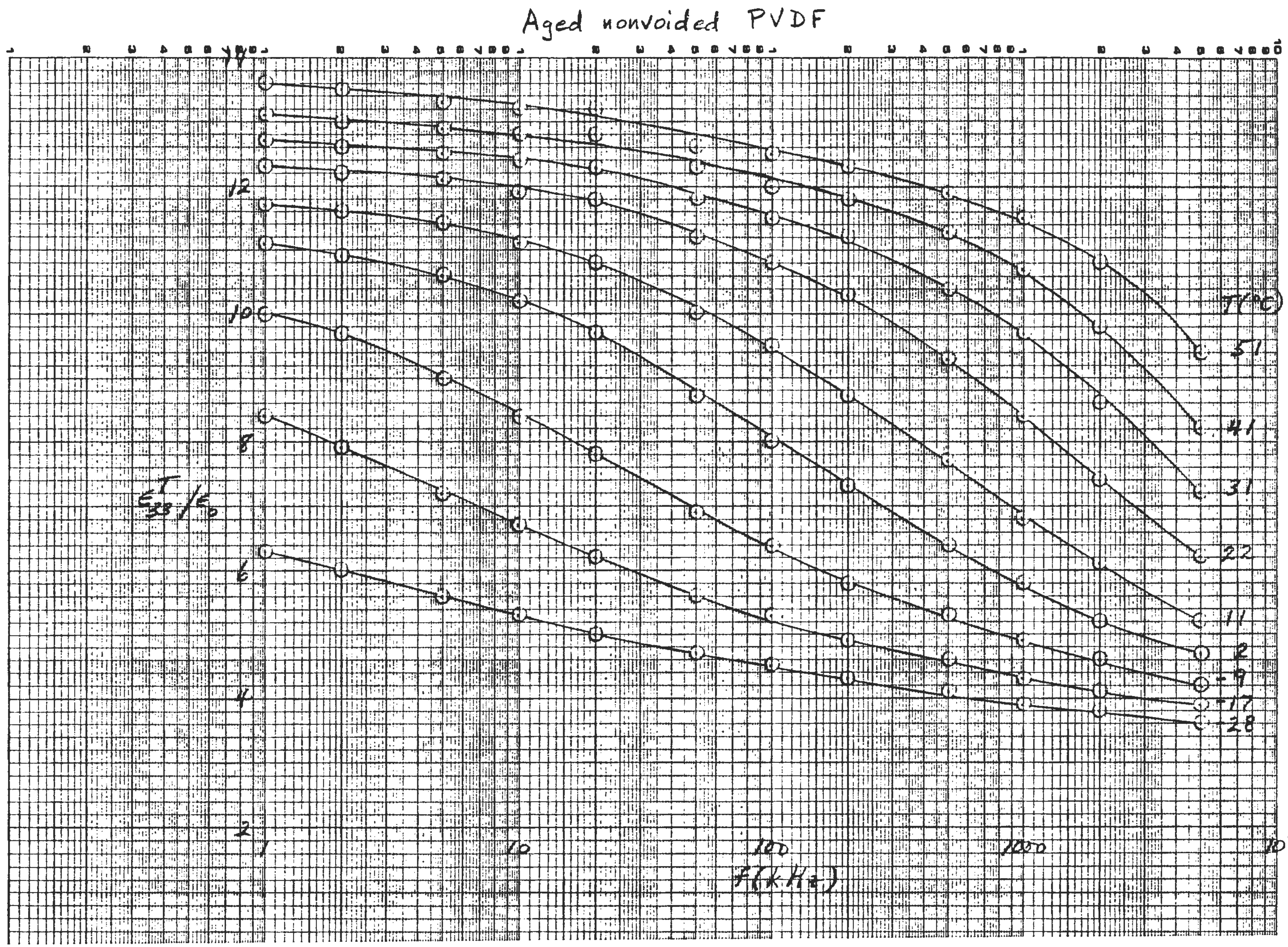


Figure 3. Dielectric constant, nonvoided PVDF after exposure to 51$^{O}$C.

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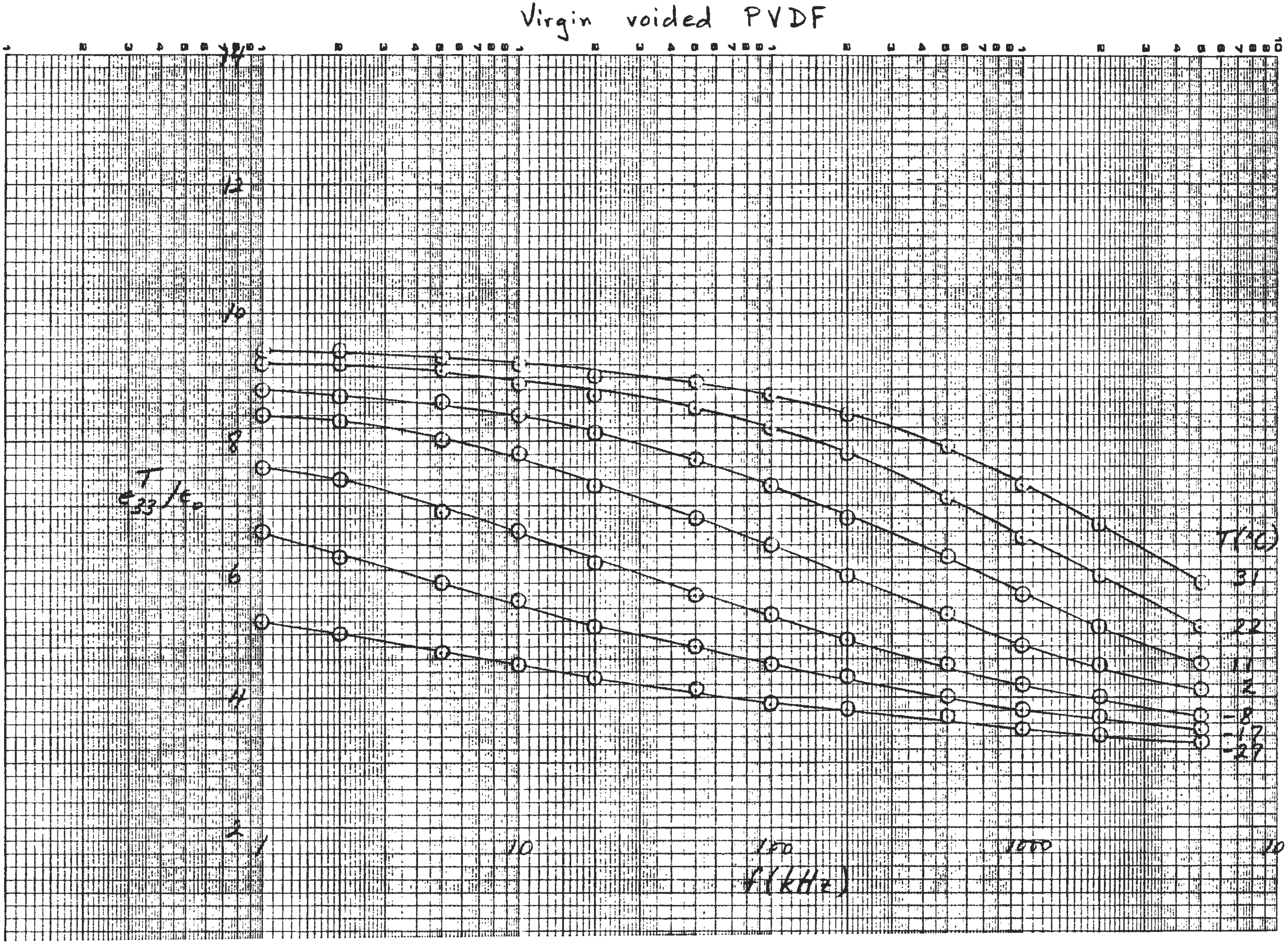


Figure 4. Dielectric constant, virgin voided PVDF.

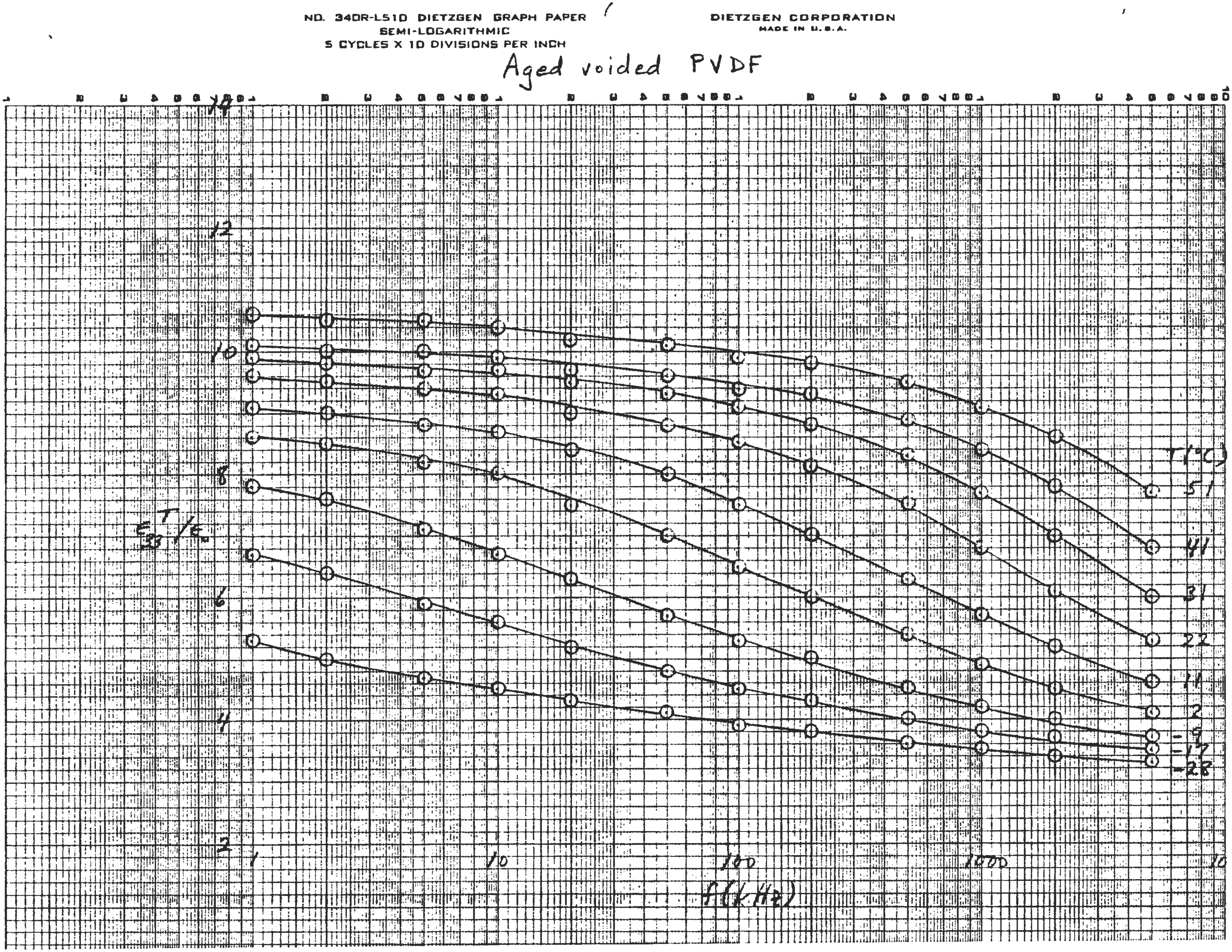


Figure 5. Dielectric constant, voided PVDF after exposure to $51^{\circ}C$.

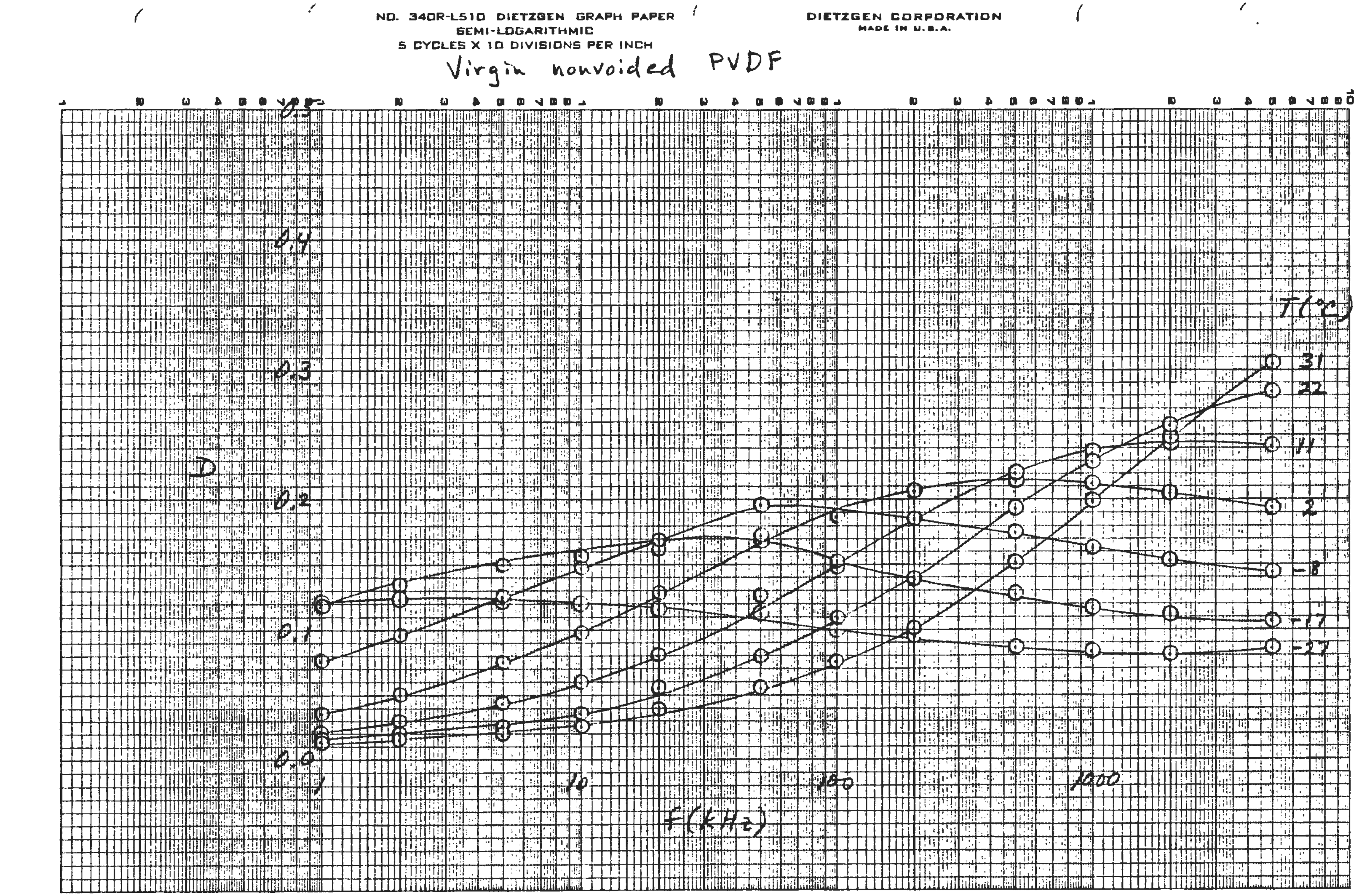


Figure 6. Dissipation factor, virgin nonvoided PVDF.

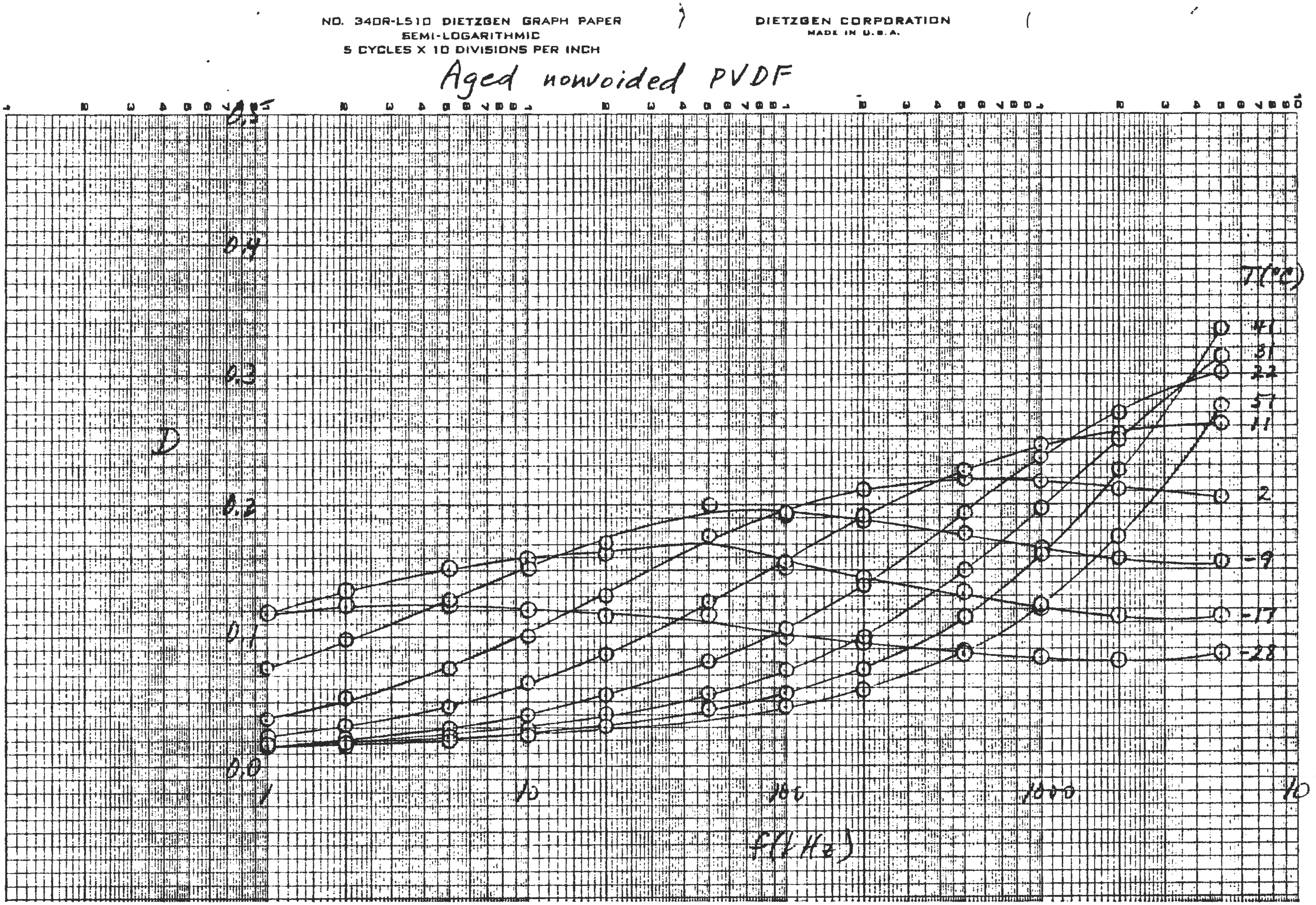


Figure 7. Dissipation factor, nonvoided PVDF after exposure to 51$^{O}$C.

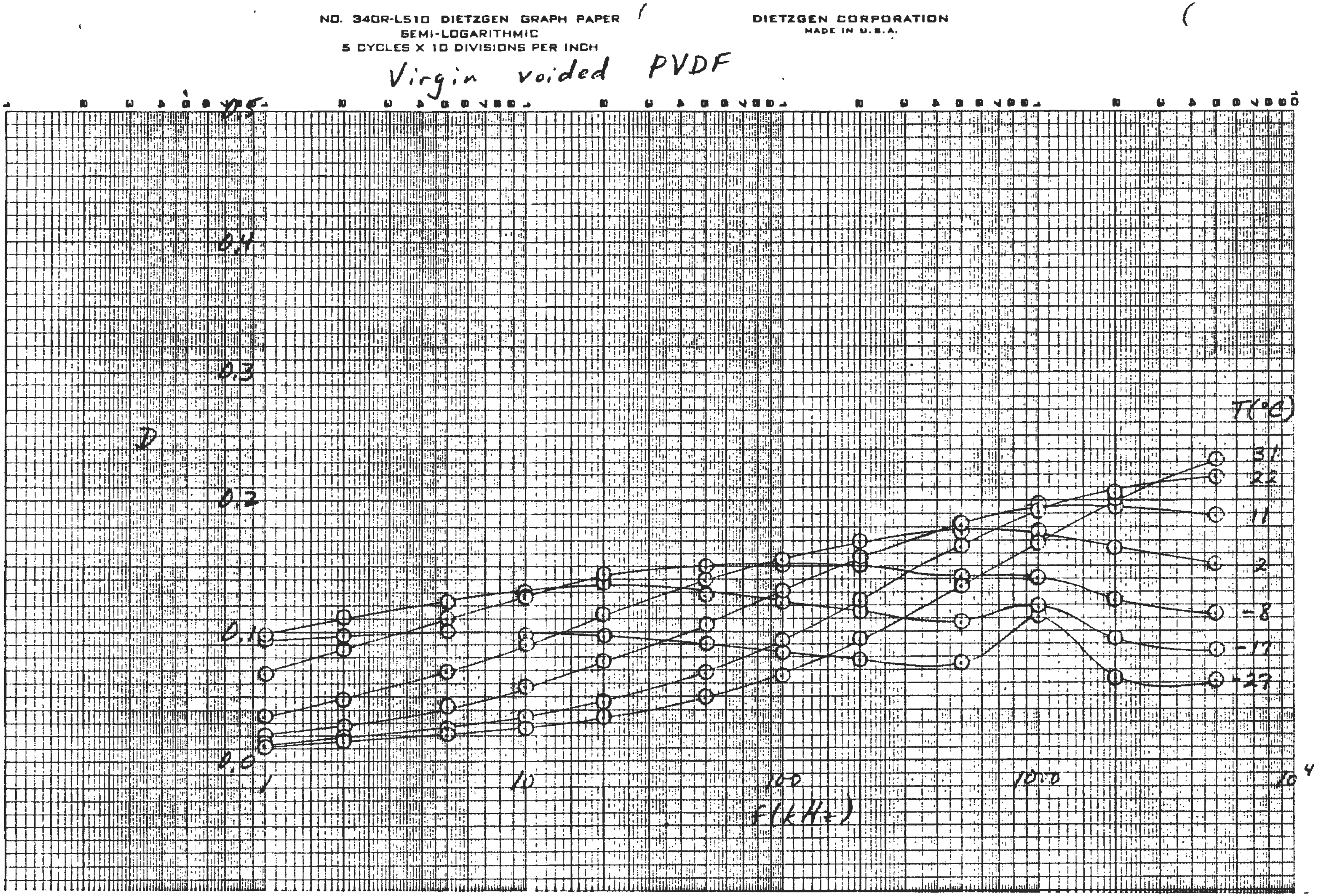


Figure 8. Dissipation factor, virgin voided PVDF.

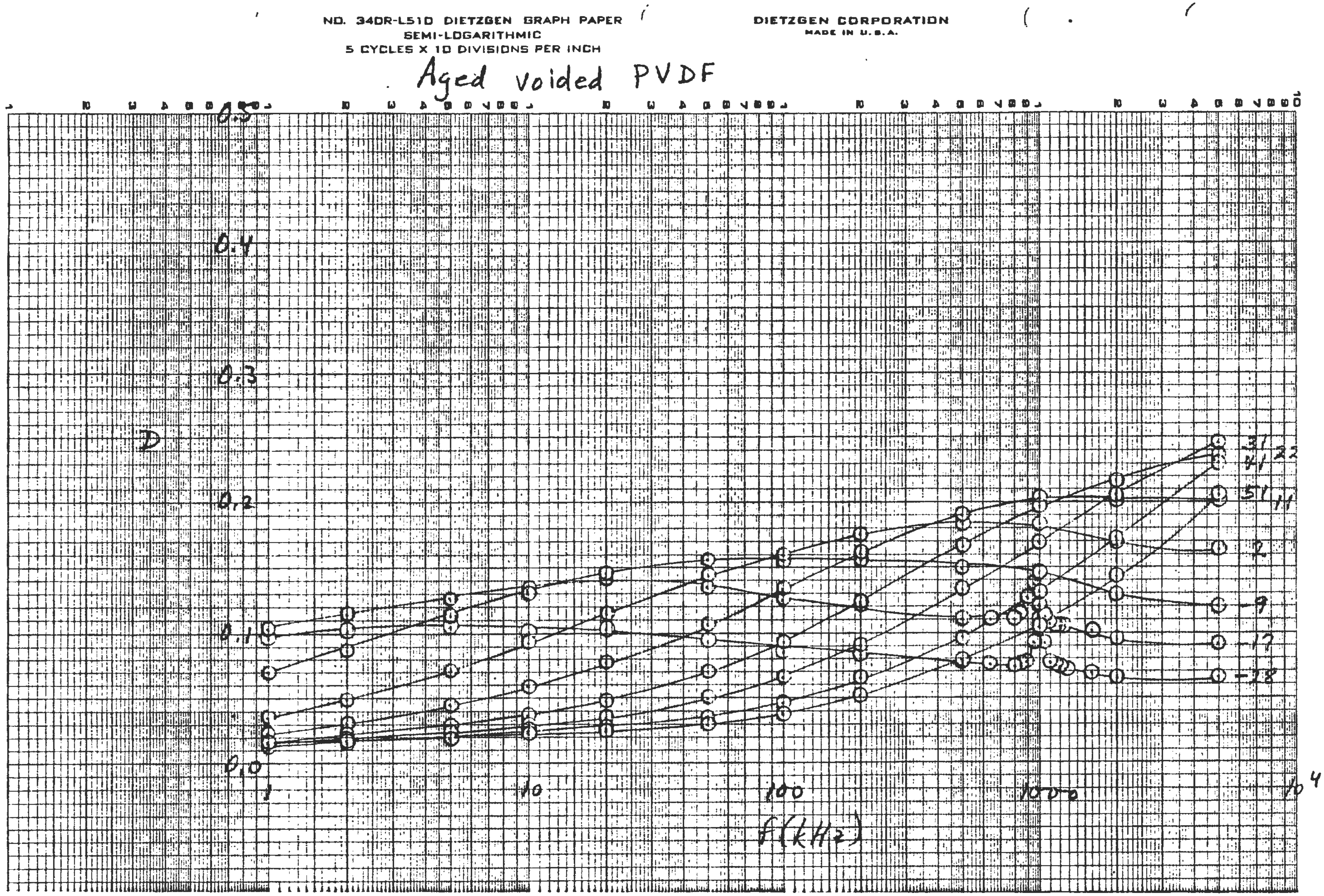


Figure 9. Dissipation factor, voided PVDF after exposure to 51°C.

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Mark B. Moffett
Target Physics Sensor Technology Branch
James M. Powers
Electroacoustic Transduction Branch
TM No. 841072
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